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14. ABSTRACT
Jaffe (1967) and Mitchel et al. (1972) have succeeded in determining the lower-bound bearing strength of lunar soils from images obtained during the Apollo lunar missions. This was achieved through assessing the lunar soil friction angles from slope angles in craters and traces, and was based on Terzaghi's ultimate bearing capacity (Terzaghi, 1943). Most recent advances in topography mapping using photogrammetry with resolutions in the order of single centimeters encourage that the method presented by Jaffe (1967) and Mitchel et al. (1972) can be modified for cohesionless sandy sediments to derive lower-bound bearing strength from topographies mapped using an Unmanned Aerial Vehicle (UAV) in foreshore environments.
The goal of the proposed study is to develop and test an approach to derive lower-bound bearing strength of sandy foreshore sediments from aerial digital images. This would allow a rapid estimate of minimum bearing strength, and thus, the potential of the sediment to support vehicles. The scientific objectives to achieve this goal are to (i) derive sand type, angle of repose and state of saturation from digital imaging processing, (ii) determine lower-bound bearing strength using an approach successfully applied by Jaffe (1967) and Mitchell et al. (1972) for the characterization of lunar soils from images from the Apollo lunar missions, and (iii) create a map of zones of low vs. high lower-bound bearing strength from the image coverage.

15. SUBJECT TERMS

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Rapid Assessment of Lower Bound Bearing Strength for Foreshore Sediments using Aerial Digital Images

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LONG-TERM GOALS

The long-term objective is to develop an approach to assess the lower bound bearing strength of foreshore sediments from remote sensing and aerial digital images to assist with beach trafficability assessments.

OBJECTIVES

The primary objective is to develop, test, and optimize an approach to derive friction angles, state of saturation, and sand type from remote sensing, and derive lower bound bearing strength from these properties to create foreshore bearing strength maps remotely and rapidly.

APPROACH

Foreshore images will be collected using satellite panchromatic and multispectral imagery, satellite radar, land-/ship-based radar, aerial digital images, land-/ship-based digital imagery. Foreshore topographic features of different scales will be resolved using shadows and photogrammetry. Friction angles will be derived from the topographic features. Sediment type and saturation will furthermore be assessed based on color, shading, and reflectivity. From these information the lower bound friction angle will be determined, following the approach by Jaffe (1965) developed for the lunar Apollo mission. From the lower bound friction angle, lower bearing strength can be derived using Terzaghi (1943) and Jaffe (1965), and will be utilized to create a foreshore map of zones of low and high bearing strength. Such a map could serve as a recommendation for beach trafficability assessments. Two field experiments will be conducted in the framework of this project to provide a proof-of-concept of the proposed approach, and assess the required characteristics of the remotely obtained data. One field experiment was conducted at the U.S. Army Corps of Engineers field research facility (USACE FRF) in Duck, NC, in close collaboration with Jesse McNinch, Heidi Wadman (both USACE FRF, Duck, NC), and Hans Graber (RSMAS, Miami, FL). This field experiment included all remote sensing and imaging techniques as listed above, in-situ geotechnical testing and sampling. The second field experiment will focus on aerial digital imagery using different types of Unmanned Aerial Vehicles (UAVs), geotechnical testing and sampling, and will be carried out at Claytor Lake State Park, VA. The PI will be supported here by the Mid-Atlantic Aviation Partnership (MAAP) at Virginia

Tech, and the Division of State Parks, VA. The field experiments will also include physical sediment sampling and sand cone testing (ASTM D1556) to assess in-situ sediment bulk density. Field data will be compared to conventional friction angle assessments based on physical sediment sampling and laboratory testing. Laboratory tests will include tilt table tests to determine the angle of repose under controlled conditions, and direct shear testing (ASTM D3080), representing a standard geotechnical laboratory method to determine friction angles of sands.

WORK COMPLETED

i) Field Experiment I

The first field experiment was successfully completed during the period of 20-26 September 2016 at the USACE FRF in Duck, NC. The following components were completed:

Test	transects/locations	days/duration
Remote sensing & imagery		
Aerial and land-based digital images	Northern & Southern Beach (incl. targets)	21-24 & 26 Sept
SWIFT radar (static mode)	Southern Beach (incl. targets)	21, 23, 26 Sept
Satellite images (panchromatic & multispectral)	Northern & Southern Beach (incl. targets)	24 Sept
Satellite radar images	Northern & Southern Beach (incl. targets)	20-23 & 26 Sept
Topography		
RTK GPS large-scale	Southern Beach (incl. targets)	21-24 & 26 Sept
RTK GPS small-scale	Southern Beach	21,23 & 26 Sept
Target photogrammetry	Southern Beach (incl. targets)	21-24 & 26 Sept
Target measurements	Southern Beach (incl. targets)	21-24 & 26 Sept
Geotechnics		
Sediment coring	Southern Beach (3 cross-shore transects)	21 & 23 Sept
Sediment surface characterization	Southern Beach (3 cross-shore transects)	23, 24 & 26 Sept
Sand cone in-situ density tests	Southern Beach (1 cross-shore transect)	23 Sept
Cross-shore pore pressure monitoring	Southern Beach (1 cross-shore transect)	22-24 Sept
Vertical pore pressure monitoring	Southern Beach	24-26 Sept
Nearshore pore pressure dissipation tests	Southern Beach (1 cross-shore transect)	22 Sept
Nearshore to foreshore in-situ strength testing	Southern Beach (1 cross-shore transect)	22,23,24 & 26 Sept
Nearshore grab sampling	Southern Beach (1 cross-shore transect)	22,23 & 24 Sept

All measurements as listed above were successfully completed (see examples in Fig. 1 and 2). Data processing has been completed.

Figure 1. Examples of targets created of native sediments, including pits and mounts of different size.

ii) Field Experiment II

The second field tests was performed at Claytor Lake State Park Beach, VA, on 25-26 October 2016. Two UAVs were tested, but most flights were carried out using the SkyRanger, operated by trained pilots of MAAP. Flights were performed at flight heights of 15 m, 30 m, 60 m and 120 m, with low and high image overlap. A control duplicate flight was performed at 30 m flight height with high image overlap. A flight with infrared imaging was performed at a flight height of 30 m. Sediment samples were taken along two cross-shore transects, and were complemented by sand cone testing. Initial image photogrammetry was performed using the commercial software Pix4D. Advanced analysis was carried out using Matlab. Image processing has been completed. Geotechnical laboratory testing of sediment samples included tilt table testing, and direct shear testing. All tests and data analysis has been completed.

Figure 2. Panchromatic satellite image showing the foreshore and targets on 24 September 2016.

iii) Geotechnical Laboratory Analysis

For tilt table testing, a sand paper surface was created from the sediment samples as the bottom plate of the tilt table, and sediment sample masses ranging from 100-200 g were loosely poored onto the plate. The plate was then slowly tilted, and angles of noticeable sediment movement were read. For each angle read, the mass of sediment slipped was recorded. The angle of repose was considered achieved if at least 50% of the sediment slipped. The impact of moisture content was preliminarily tested by testing dry sediment, and sediment with a moisture content of 10%.
Direct shear testing was performed according to ASTM D3080 at normal stresses of 24 kPa, 48 kPa, and 72 kPa. While these tests represent one of the most common method to test the friction angle of sands, it should be mentioned that differently than the investigated conditions in the field, and the tests on the tilt table, these tests can only be performed under sediment confinement.

iv) Publication

A manuscript titled "Lower bound bearing strength at sandy beaches from remote imagery" was submitted to *Geotechnique Letters* on May 22nd, 2017 (Fig. 3). The manuscript is currently in review. The PI expects that two more manuscripts will result from the collected data, and at least one conference presentation. With regard to the latter, an abstract submission to the *AGU Fall Meeting 2017* is planned.

RESULTS

The sand at Claytor Lake state park is classified as a poorly graded sand with d_{50} = 286-610 μm, and with C_u= 1.81-3.11 and C_c= 0.91-1.07 for five representative cross-shore samples at a distance of 0.5-20 m from the shoreline at the survey date. The in situ unit weight as measured with the sand cone test ranged from γ_i = 16.5-18.7 kN/m^3, while the values determined from a carefully extracted push core sample were generally higher at γ_i = 17.7-21.1 kN/m^3. The sand at Duck is classified as a poorly graded sand with d_{50} = 347-1358 μm, and with C_u= 1.8-7.2 and C_c= 0.51-1.7 for five representative cross-shore locations along a transect spreading from the foot of the dune toe to the low water line (approximately zero Mean Lower Low Water). The in situ unit weight as measured with the sand cone test ranged from γ_i = 16.2-20.8 kN/m^3, while the values determined from a carefully extracted push core sample were in a similar range at γ_i = 17.5-20.0 kN/m^3. Photogrammetric reconstruction of sand pits and mounds at Duck, NC, and of small-scale morphological features such as foot steps at Claytor Lake, VA, suggested

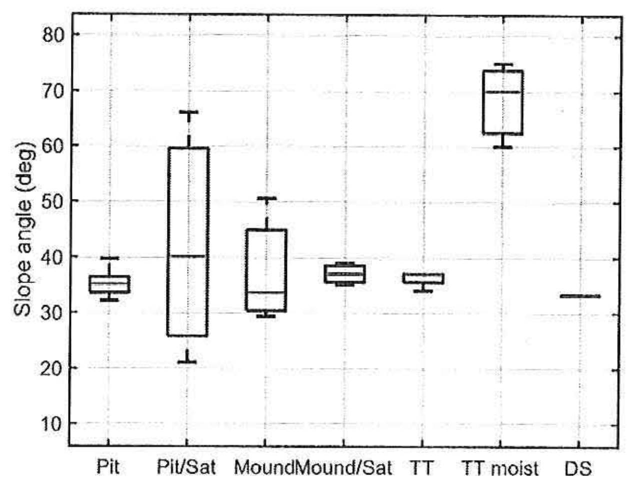

Figure 3. Statistics of determined slope and friction angles from Duck, NC, with from the left to the right: slope angles from photogrammetric analysis of sand pits, slope angles from satellite image analysis of sand pits, slope angles from photogrammetric analysis of sand mounds, slope angles from satellite image analysis of sand mounds, the angle of repose (equaling the maximum natural slope angle) from tilt table testing, the angle of repose of moist sediment from tilt table testing, and the angle of internal friction from confined direct shear testing (Stark et al., *in review*)

average slope angles of ~34-37° at Duck (Fig. 3), and of ~42° at Claytor Lake. Slope angles determined from satellite images at Duck ranged from ~26-60° with a mean of ~40° for sand pits, and from ~30-45° with a mean of 34° for sand mounds. Tilt table testing of sediments from Duck suggested an angle of repose of ~38° for dry sand, and ~70° for moist sand. Direct shear testing suggested an angle of internal friction of ~33°, suggesting that the internal angle of friction (as needed for standard bearing capacity measurements) is equal to 0.9 times the slope angles determined from remote sensing. Similar trends were observed at Claytor Lake with a larger impact of coarse sharp-angled particles mixed in the sediment, leading to overall higher friction angles if abundant. The slope angles determined from remote imagery, and the comparison to laboratory testing match well theoretical expectations.

While assumptions were made, and this study was restricted both to the dry sand zone of the foreshore and to individual topographic features, it has been shown that loose sand friction angles can be determined from random, multiple perspective images of topographic features, as well as UAV digital imagery. Furthermore, first attempts to derive a rough estimate of slope angle from panchromatic satellite images were encouraging, and it is expected that a more detailed and sophisticated analysis may produce valuable results. Overall, the results provide a successful proof-of-concept of the methodology. Significant next steps should include: (a) a more detailed investigation of moisture content from partial to full saturation; (b) a sensitivity analysis regarding the number of features, types of features and number of slopes per feature used for analysis; (c) the use of different remotely sensed signals (e.g., visual spectrum and radar); (d) the development of a problem-based modified bearing capacity approach.

IMPACT/APPLICATIONS

The results are expected to have significant impact on the fundamental understanding of the correlation between geotechnical sediment properties and foreshore morphology. The developed approach, as well as the gathered knowledge, will be directly applicable to beach trafficability problems, and other issues of foreshore sediment stability, such as coastline erosion, extreme events, and beach nourishment.

RELATED PROJECTS

N00014-17-1-2516; N00014-16-1-2631.

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